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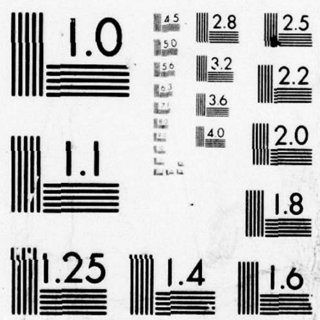

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FINAL TECHNICAL REPORT

HIGH NA SINGLE MODE FIBER

15 SEPTEMBER, 1978 TO 15 MARCH, 1979

CONTRACT NO. N00173-78-C-0196

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HIGH NA SINGLE MODE FIBER

Final Report

15 September 1978 to 15 March 1979

Contract No. N00173-78-C-0196

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Single mode fibers offer a useful medium for new sensor applications based on optical phase change detection. Examples are the optical gyroscope and temperature and accoustic sensors. Many of these applications require the single mode fiber to be used in a tightly coiled configuration. One limiting factor in sensor development is that single mode fibers with a numerical aperture (NA) of <.15 exhibit a sharp increase in attenuation when subjected to bending and microbending. To overcome this limitation, the development of a high NA (>.15) single mode fiber was started under contract N00173-78-C-0196 to achieve improved handling and performance. less than greater than

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characteristics with respect to reduced bending and microbending losses.

Single mode fibers with numerical apertures = 0.2 were developed using core compositions of SiO_2/GeO_2, $SiO_2/GeO_2/P_2O_5$, and SiO_2/P_2O_5 and a B_2O_3/SiO_2 cladding, and fabrication techniques were investigated which minimize the central index dip in the core of these fibers.

The high NA fibers were evaluated for optical attenuation strung and spooled, at wavelengths of 0.63, 0.83 and 1.03 µm. In contrast to 0.1 NA single mode fibers which do not transmit when spooled, high NA fibers showed no significant attenuation increase when wound onto 10 cm diameter spools. Fiber attenuation was found to increase as a function of numerical aperture from 2.57 dB/km for a 0.1 NA fiber, to 16.6 dB/km for a 0.23 NA fiber at 0.83 µm evaluation wavelength. Selected single mode fibers showed variations in mean tensile strength from 1414 N/mm^2 to 5413 N/mm^2 with N values of 7.5 and 55 respectively. Fibers were fatigue tested and found to have an average N value of 22.

micron

Sq. mm

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1.0 INTRODUCTION

Single mode fibers offer a useful medium for new sensor applications based on optical phase change detection. Examples are the optical gyroscope, and temperature and accoustic sensors. Many of these applications require the single mode fiber to be used in a tightly coiled configuration. One limiting factor in sensor development is that single mode fibers with a numerical aperture (NA) of <.15 exhibit a sharp increase in attenuation when subjected to bending and microbending. To overcome this limitation, the development of a high NA (>.15) single mode fiber was started under contract N00173-78-C-0196 to achieve improved handling and performance characteristics with respect to reduced bending and microbending losses.

For single mode fibers, the relationship between fiber NA and bending and microbending losses has been established in theory and verified in practice. In order to reduce bend losses a program was started at ITT EOPD under contract N00173-78-C-0196 to develop high NA single mode fibers with the following objectives:

- o Development of preforms and optimization of core and cladding compositions to achieve a NA = 0.2.

- o Fabrication of preforms and fibers which consist of the optimized composition.

- Evaluation of fibers with respect to attenuation, bend losses, mode content, core and cladding dimensions and numerical aperture.

- Evaluation of fibers with respect to dynamic tensile strength, fatigue resistance, and long length proof test strength.

- Delivery of four fully characterized high NA single mode fiber samples.

All of the above objectives were met. Core compositions of SiO_2/GeO_2, $SiO_2/GeO_2/P_2O_5$, and SiO_2/P_2O_5 were developed and were used to fabricate high NA single mode fibers. Techniques were developed which minimized the central index dip in these fibers. The high NA fibers were evaluated for loss while strung and while spooled, at three wavelengths. In contrast to low NA single mode fibers these high NA fibers showed no significant attenuation increase when wound onto 10 cm diameter spools. Fiber attenuation was found to increase as a function of numerical aperture. Selected fibers were evaluated with respect to tensile strength and fatigue resistance. Four high NA single mode fiber samples representing each of three core composition types were delivered to NRL. Section 2 discusses in detail the developmental effort and results achieved with high NA single mode fiber.

2.0 HIGH NA SINGLE MODE FIBER DEVELOPMENT

ITT EOPD is currently producing single mode fibers for a variety of customer specifications for NA, loss, core size, and fiber diameter. For example, the EOPD Type T-110 single mode fiber has a NA of 0.10 and a core diameter of 4.5 μm. Attenuation values as low as 2 dB/km at 0.85 μm have been achieved for this fiber when measured under minimum microbending conditions. However, the optical loss increases substantially when the fiber is measured on a spool or when coiled. To reduce these bend and microbend losses, preforms had to be developed with glass compositions which result in a NA = .2. No difficulties were encountered in increasing the NA from .1 to .2; however, fabrication factors such as deposition temperature, collapse temperature, central index dip, and dimensional control, as well as achievement of optical and mechanical specifications required detailed investigation. The following section describes the design, development and evaluation of high NA single mode fibers fabricated with three different core glass compositions.

2.1 Fiber Design

A single mode fiber differs from a multimode fiber in that its normalized core size Vc must be less than the normalized cut off value of the next higher order mode which is 2.405.

Only the fundamental HE_{11} mode can propagate for values of Vc <2.405. Vc is given by:

$$Vc = \frac{dc\ \pi(n_2^2 - n_1^2)^{\frac{1}{2}}}{\lambda} \qquad (1)$$

where: dc = core diameter

λ = operating wavelength

n_2, n_1 = refractive indices of the fiber core and cladding respectively

The NA refractive index relationship is defined as:

$$NA = (n_2^2 - n_1^2)^{\frac{1}{2}} \qquad (2)$$

The HE_{11} mode has no cutoff, but as Vc becomes smaller, the normalized mode diameter increases such that the mode becomes more weakly guided and becomes highly susceptible to bending and microbending losses. In practice, values of Vc >.8 Vco are selected in order to reduce bend loss sensitivity. Thus, in designing a single mode fiber, the NA and the core diameter must be chosen so that the requirement for Vc is met.

An additional consideration is that as $\Delta n/n$ or NA becomes small, the single mode fiber becomes highly susceptible to bending losses, but as $\Delta n/n$ increases from 0.2% to 0.8%, a factor of four reduction in bending losses is theoretically predicted. A goal NA of 0.2 was chosen, which corresponds to a $\Delta n/n$ value

of 0.93%. The index difference, Δn, is achieved by reducing the cladding index or by raising the core index or both. Typically, B_2O_3 is added as a dopant to reduce the cladding index while the core index is altered by the addition of GeO_2, or P_2O_5 or both. Since an increase in dopant level usually leads to an increase in Rayleigh and nonRayleigh scattering losses of the core glass, the addition of core dopants was minimized. To produce a Δn of 0.93% with minimal core doping the cladding refractive index was lowered to the theoretical minimum index by doping the cladding with 15% B_2O_3. Because an appreciable portion of the light power propagates in the cladding material of a single mode fiber, the thickness of the cladding was designed to be at least 10 times the core radius. This insured that most of the field is contained within the deposited cladding material and that inward diffusion of impurities from the starting substrate has a minimum effect on optical transmission. With the selection of a fiber NA of 0.2 and a Vc of 2.2 (90% Vco), equation (1) specified a single mode fiber core diameter of 2.2 μm.

2.2 Fabrication Technique

Fiber preforms were fabricated by the modified chemical vapor deposition technique, using mass flow control of chemical reactants. Bubble free high purity natural fused quartz tubing was used for the substrate material, into which optical

cladding and core materials were deposited. Typically, fifty layers of cladding and four layers of core materials were deposited giving a nominal cladding to core ratio of greater than 10:1. The thick cladding layer also permitted the use of standard size substrate tubes (15 mm OD, 12 mm ID). Also, preforms were fabricated using a Vycor® tube which functioned both as a substrate tube and as an optical cladding. Vycor® is a commercially available high silica content borosilicate glass into which core materials were directly deposited. By avoiding the long time required for deposition of borosilicate cladding, both labor and material costs were reduced. This approach proved to be highly useful for quick evaluation of NA, central index dip, and fabrication conditions. However, Vycor® preforms fabricated during the course of the contract had bubbles, inclusions and impurities and therefore were not usable for low loss single mode fiber fabrication.

A borosilicate composition having 15% B_2O_3 was chosen for the cladding since this proportion corresponds to a minimum in the refractive index composition curve. In contrast, the Vycor® tubing had about 4% B_2O_3 and a higher index of refraction than the heavily doped borosilicate cladding. After preforms were fabricated, small diameter canes were drawn which were then used to evaluate the NA and the core/clad

/ 5

ratio. The far field output pattern of the fully injected multimode cane was used to measure NA to ±.01 and an optical microscope was used to determine core/clad ratio in the cane. After the core diameter was calculated using equation (1), the core/clad ratio was utilized to determine the desired fiber diameter. The preforms were then drawn to fibers of the desired diameter with the equipment shown schematically in Figure 1. The preforms were drawn using a graphite resistance furnace. Furnace drawn fibers, in contrast to flame drawn fibers, exhibit better diameter uniformity but lower strength. The fiber diameter was monitored continuously and was controlled within ±2%. Fibers were dip coated on line with a low modulus silicone resin to a nominal diameter of 300 μm. Also, a Hytrel® jacket was extruded on-line to a nominal final diameter of 500 μm. The fibers were collected on 10 cm diameter spools as they were drawn.

2.3 Preform Development

To achieve a NA = .2 the following three glass systems were studied:

- o SiO_2/GeO_2 core - SiO_2/B_2O_3 cladding
- o $SiO_2/GeO_2/P_2O_5$ core - SiO_2/B_2O_3 cladding
- o SiO_2/P_2O_5 core - SiO_2/B_2O_3 cladding

In the following discussion, composition values are reported

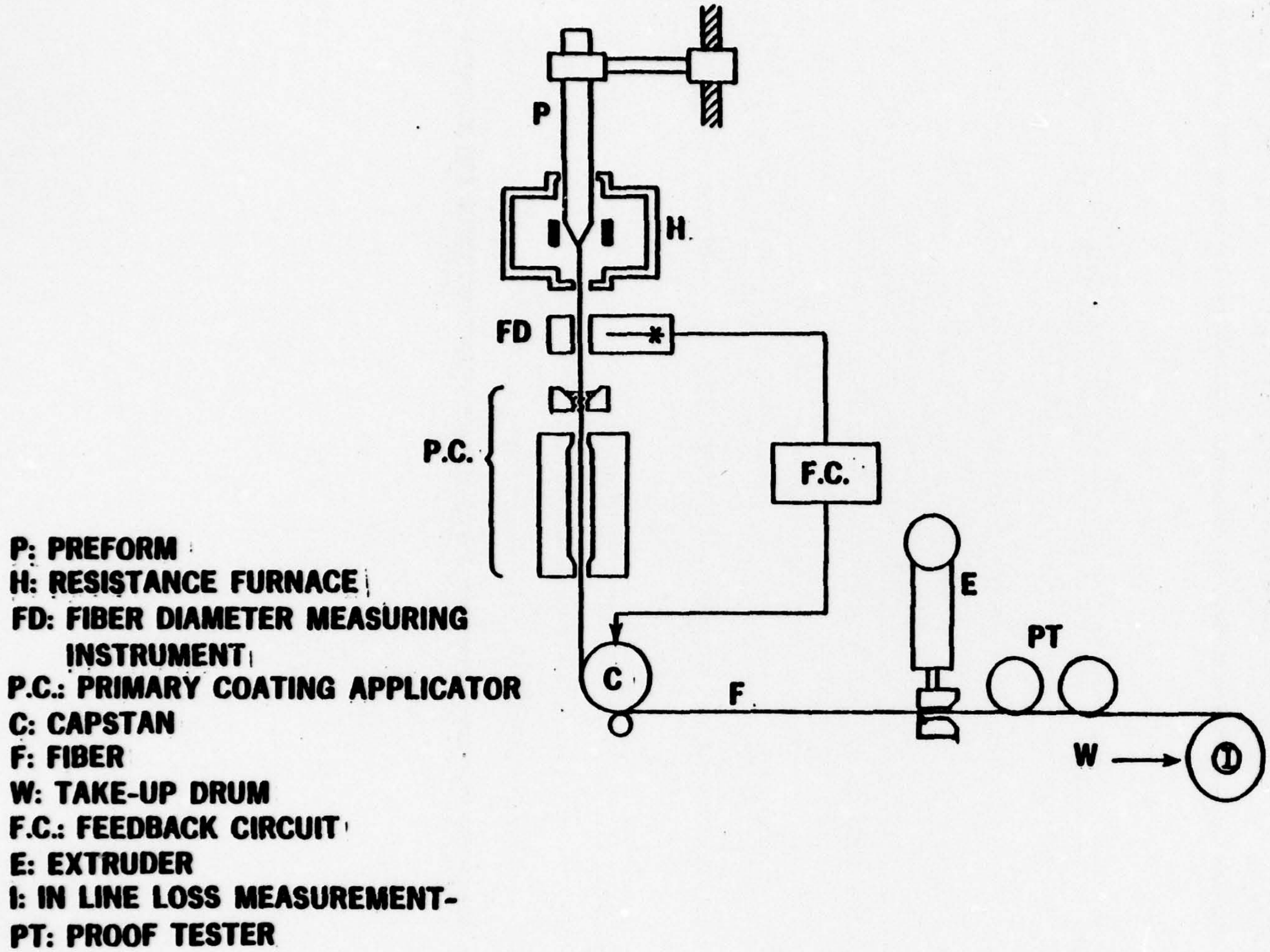

Figure 1. Optical Fiber Drawing Instrument Diagram.

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by weight percentage and assume stoichiometric yield of oxides from the chlorides of silicon and germanium and from phosphorous oxychloride.

2.3.1 SiO_2/GeO_2 Core Composition - B_2O_3/SiO_2 Cladding

The first core glass system studied was the SiO_2/GeO_2 system. The addition of GeO_2 increases the refractive index of SiO_2. Table 1 summarizes the cladding and core compositions, NA values, and core and fiber dimensions for the developmental preforms having the GeO_2/SiO_2 core composition.

Preforms EM-20407 and EM-20413, with 15% B_2O_3 cladding and virtually pure SiO_2 (4% GeO_2) core exhibited NA values of 0.16 and 0.15. Doubling the GeO_2 content in EM-20417 and quadrupling it in EM-20422 gave no measurable increase in NA. In fact, EM-20422 had a substantial reduction in NA. This reduction was linked to relatively high temperature core deposition conditions which depleted the volatile GeO_2 dopant. It was then decided to establish core deposition conditions in Vycor® substrates, which permitted us to reduce preform processing time. Preform EM-20427 was successfully fabricated using a Vycor® substrate and showed that NA values ≥.2 can be achieved. This preform also showed a relatively large dopant depletion region or central refractive index "dip." The next Vycor® preform EM-20428 gave a NA value of 0.14. When this core composition

Table 1. High NA Single Mode Fiber Development Preform Composition Optimization: SiO_2/GeO_2 Core.

Preform No.	Cladding $\%B_2O_3$	Cladding $\%SiO_2$	Core $\%GeO_2$	Core $\%SiO_2$	Passes	NA	Dimensions Core/OD (μm)
EM-20407	15	85	4	96	2	0.16	2.2/79
EM-20413	15	85	4	96	2	0.15	2.0/102
EM-20417	15	85	7	93	3	0.16	2.2/95
EM-20422	15	85	16.5	83.5	2	0.13	2.2/109
EM-20427	Vycor®		56	44	5	.21	
EM-20428	Vycor®		40	60		.14	
EM-20468	15	85	40	60	4	0.23	2.3/76
EM-20483	Vycor®		36	64	3	.12	
EM-20484	Vycor®		36	64	3	.12	
EM-20495	13.5	86.5	36	64	3	0.21	2.1/79

was deposited onto a 15% borosilicate cladding (preform EM-20468) a NA of 0.23 was achieved. However, the high percentage of GeO_2 core dopant resulted in a central dip of 0.82 μm diameter in a 2.3 μm core. This central dip was undesirable because of uncertainties it introduced to the normalized core size calculation.

As a result of the large central dip found in EM-20468, a series of experiments was performed to reduce or eliminate GeO_2 depletion during collapse. Three techniques were evaluated:

1. Following deposition of the cladding layer, the preform was partially collapsed leaving a small diameter bore. The core was then deposited, and the preform was collapsed completely.

2. During collapse, small amounts of $GeCl_4 + O_2$ were passed through the tube to replace evaporated GeO_2.

3. During collapse, a slight pressure of O_2 was maintained inside the tube to force the $2\ GeO_2 \rightarrow 2\ GeO + O_2$ equilibrium toward the formation of less volatile GeO_2 glass.

Technique 1 was found to be most effective in reducing the central dip, and was therefore used throughout the program for preform fabrication. An undesirable effect of this collapse technique was that preforms became unstable after the initial collapse pass, due to thermal expansion mismatch of substrate and cladding glasses. After two successive preforms shattered during core deposition the B_2O_3 concentration in the cladding was reduced from 15% to 13.5%. Preform EM-20495 was produced which

met the NA = .2 requirement. The central dip in EM-20495 was about 0.4 μm in diameter, which corresponded to one-half the dip diameter in EM-20468. Preforms EM-20484 and EM-20495 showed that a NA value of 0.12 in Vycor® corresponded to a NA of 0.2 if the core compositions were deposited in a 13.5% B_2O_3 borosilicate cladding.

2.3.2 $SiO_2/GeO_2/P_2O_5$ Core Composition - B_2O_3/SiO_2 Cladding
The contract study was continued by next investigating the $SiO_2/GeO_2/P_2O_5$ core glass system. The addition of P_2O_5 to SiO_2 is known to both increase the refractive index and to aid deposition by lowering the softening temperature. Table 2 summarizes the parameters investigated in the development of high NA fibers using the $SiO_2/GeO_2/P_2O_5$ core composition.

Vycor® substrates were used to establish chemical flow rates and fabrication parameters; an NA of 0.12 was the goal. Preforms EM-20511 and 20512 failed because the core glass composition had a very low softening point. During collapse, the core glass melted ahead of the moving torch and sealed the substrate tube. The P_2O_5, GeO_2, and SiO_2 concentrations were then adjusted to give the desired NA of 0.12 in the Vycor® cladded fiber. Once core fabrication conditions were estabished, two preforms were made using a deposited borosilicate cladding having 13.5% B_2O_3. Preforms EM-20533 and EM-20536 had NA values of 0.18 and 0.19 respectively. Cane micrographs showed a barely

Table 2. High NA Single Mode Fiber Development
Preform Composition Optimization
$SiO_2/GeO_2/P_2O_5$ Core.

Preform No.	Cladding %B_2O_3	Cladding %SiO_2	Core %P_2O_5	Core %GeO_2	Core SiO_2	Passes	NA	Dimensions Core/OD (μm)
EM-20511	Vycor®		17	18	65	3		Collapse Failure
EM-20512	Vycor®		9	20	71	4		Collapse Failure
EM-20519	Vycor®		2	34	64	4	.22	
EM-20520	Vycor®		2	18	80	4	.10	
EM-20523	Vycor®		2	20	78	4	.12	
EM-20533	13.5	86.5	2	20	78	4	.18	2.5/71
EM-20536	13.5	86.5	2	20	78	4	.19	2.3/106
EM-20545	Vycor®		4	16	80	4	.12	

visible depletion dip. The effect of P_2O_5 on NA was marked. As shown in Table 1, preform EM-20495 had a GeO_2 percentage of 36% in SiO_2, while EM-20536 achieved a similar NA with 20% GeO_2 and 2% P_2O_5 in a $SiO_2/GeO_2/P_2O_5$ core. This effect was attributed to reduced dopant vaporization during deposition, since the addition of P_2O_5 reduces the softening point and allows a lower deposition temperature to be used.

The $SiO_2/GeO_2/P_2O_5$ core preforms had a smaller central dip than those produced with the SiO_2/GeO_2 core. EM-20545 was fabricated with a 4% P_2O_5 content $SiO_2/GeO_2/P_2O_5$ core to study the effect of P_2O_5 dopant level on central dip. The central dip in this preform was larger than the dip in EM-20536 which had 2% P_2O_5 in the core.

2.3.3 SiO_2/P_2O_5 Core Composition

The third core glass composition studied was the SiO_2/P_2O_5 system. The addition of P_2O_5 to SiO_2 increases the refractive index. Table 3 summarizes the development of single mode fiber preforms having SiO_2/P_2O_5 core composition. Dependence of NA on fabrication conditions for this glass system proved to be greater than anticipated. Vycor® substrate preform EM-20546 had the desired NA of 0.12, and had a negligible central dip. The corresponding preform EM-20554 with borosilicate cladding had a NA of 0.17. Doubling the P_2O_5 concentration to 16%

Table 3. High NA Single Mode Fiber Development Preform Composition Optimization: SiO_2/P_2O_5 Core.

Preform No.	Cladding $\%B_2O_3$	Cladding $\%SiO_2$	Core $\%P_2O_5$	Core $\%SiO_2$	Passes	NA	Dimensions Core/OD (μm)
EM-20546	Vycor®		8	92	4	.12	
EM-20554	13.5	86.5	8	92	4	.17	2.6/153
EM-20586	13.5	86.5	10	90	7	.16	6/116
EM-20588	13.5	86.5	13	87	8	.18	2.5/75
EM-20596	13.5	86.5	16	84	8	.19	2.3/72
EM-20604	13.5	86.5	20	80	8	.16	2.8/76

resulted in a 0.19 NA preform, EM-20596.

Although the four pass core deposition was successful, it did not allow precise control of the core diameter. In an effort to achieve greater control over the core to fiber OD ratio, a series of preforms, EM-20586 through EM-20604 (Table 3) was made with a reduced chemical flow rate and an increased number of deposition passes. The core diameter control improved by a factor of two. When deposition flow rates are changed as above, the optimum glass fusion temperature also changes. These variations in deposition conditions in turn cause changes in dopant concentration and ultimately result in NA variations. Thus, changing chemical flow rates for EM-20586 resulted in a reduction in its NA although the theoretical percentage of P_2O_5 dopant was increased.

2.4 Evaluation

Preforms and fibers were fully evaluated with respect to optical, dimensional, and mechanical properties. Evaluation of NA and core/clad ratio were discussed in Section 2.2. This section discusses the evaluation of mode content, attenuation, fiber dimension, tensile strength and fatigue resistance.

2.4.1 Optical Evaluation

Single mode fibers were examined first for mode content by injecting a multimeter length with a HeNe (λ = .6328) or Kr (λ = .6471) laser and observing the far field output pattern. A gaussian pattern which was not sensitive to injection conditions indicated single mode operation.

Optical loss was evaluated at three wavelengths, 0.63, 0.83, and 1.03 μm using an incoherent source filtered to 0.01 μm bandwidth, and at 0.6328 μm using a HeNe laser. The loss was measured with the fiber "spooled" on a 10 cm diameter spool, and remeasured when the fiber was "strung" between two 30 cm diameter drums spaced 10 m apart. A comparison of the loss results from the two measurement conditions qualitatively indicates the degree of microbending loss susceptibility of the fiber.

Results of the spooled and strung fiber loss measurements are summarized in Table 4. For comparison, an EOPD Type T-110 .1 NA single mode fiber is listed in Table 4. The T110 fiber also has a GeO_2/SiO_2 core. When comparing values, it is important to remember that the single mode spectral loss curve is roughly "U" shaped and will be shifted to lower or higher wavelengths depending on the actual value of Vc achieved for a given fiber. In contrast to the 0.1 NA fiber which exhibits

Table 4. High NA Single Mode Fiber Development: Optical Loss Characteristics.

Preform No.	Cane NA	Attenuation ±0.3 dB/km 0.63 μm Spool	0.63 μm Strung	0.83 μm Spool	0.83 μm Strung	1.03 μm Spool	1.03 μm Strung
				SiO_2/GeO_2 Core Type			
EM-20407	0.16	16.9	16.2	NT	7.0	NT	NT
EM-20413	0.15	13.3	14.1	8.9	6.0	NT	22.4
EM-20417	0.16			NT - TRANSMISSION VARIATIONS			
EM-20422	0.13	NE	NE	NE	NE	NE	NE
EM-20468	0.23	40.9	44.0	17.0	16.6	10.9	9.6
EM-20495	0.21	21.0	20.2	8.0	8.7	7.8	5.0
EM-20222*	0.10	NT	5.4	NT	2.6	NT	9.7

NT= No detectable transmission

NE= Multimode at 0.63 μm, no further evaluation

*(For reference only, EOPD Type T-110 single mode fiber)

Table 4. High NA Single Mode Fiber Development: Optical Loss Characteristics. (Continued)

Preform No.	Cane NA	Attenuation ±0.3 dB/km 0.63 μm Spool	0.63 μm Strung	0.83 μm Spool	0.83 μm Strung	1.03 μm Spool	1.03 μm Strung
$SiO_2/GeO_2/P_2O_5$ Core Type							
EM-20533	0.18	NT	26.0	10.0	10.3	7.1	5.9
EM-20536	0.19	18.8	NE	11.9	NE	9.7	NE
SiO_2/P_2O_5 Core Type							
EM-20554	0.17	9.2	NE	NE	NE	NE	NE
EM-20586	0.16	NE	13.8	NE	8.7	NE	5.8
EM-20588	0.18	NT	NT	10.6	10.7	7.4	7.5
EM-20596	0.19	NT	26.2 (.65)	16.7	17.1	10.1	9.3
EM-20604	0.16	25.02	24.7 (.65)	12.1	12.5	NT	7.8

NT = No detectable transmission

NE= Multimode at 0.63 μm, no further evaluation

high loss when spooled, fibers with NA values as low as 0.16 such as EM-20407 and EM-20413 show virtually no spooling losses at short wavelengths. These same fibers show an increased loss at 1.03 μm and spooling induced losses at 0.83 and 1.03 μm. This behavior is explained by the reduction in Vc as λ increases; that is, as the mode diameter becomes large, it becomes weakly guided and susceptible to bending and microbending losses. Fibers EM-20468 and EM-20495 had NA values of 0.2 or greater and showed little, if any, spooling losses over the entire evaluation range. Results were similar for all three core type fibers. These results dramatically validate the high NA approach for reducing bending losses in single mode fibers.

The fiber loss was also measured as a function of injection NA and the results are listed in Table 5. Some minor variations in loss versus injection NA were detected, primarily at short wavelength in the strung fiber. Since these variations were small, the 0.243 injection NA was used for the remainder of this program.

Also, the fiber attenuation was related to NA. Figure 2 shows the attenuation at 0.83 μm for the three core types as a function of NA. The trend shown here is greater than would be predicted from the intrinsic optical losses. High NA is achieved by the addition of dopants which increase intrinsic loss, but

Table 5. High NA Single Mode Fiber Development
Effect of Injection NA on Optical Loss:
Fiber EM-20413.

Injection NA	Evaluation λ (μm)	Attenuation (dB/km) Strung	Spooled
	0.63	14.3	13.1
0.243	0.83	6.3	7.4
	1.03	22.4	NT
	0.63	14.1	14.2
0.176	0.83	6.0	7.4
	1.03	22.0	NT
	0.63	11.8	13.7
0.089	0.83	5.9	7.7
	1.03	21.2	NT

NT = No detectable transmission

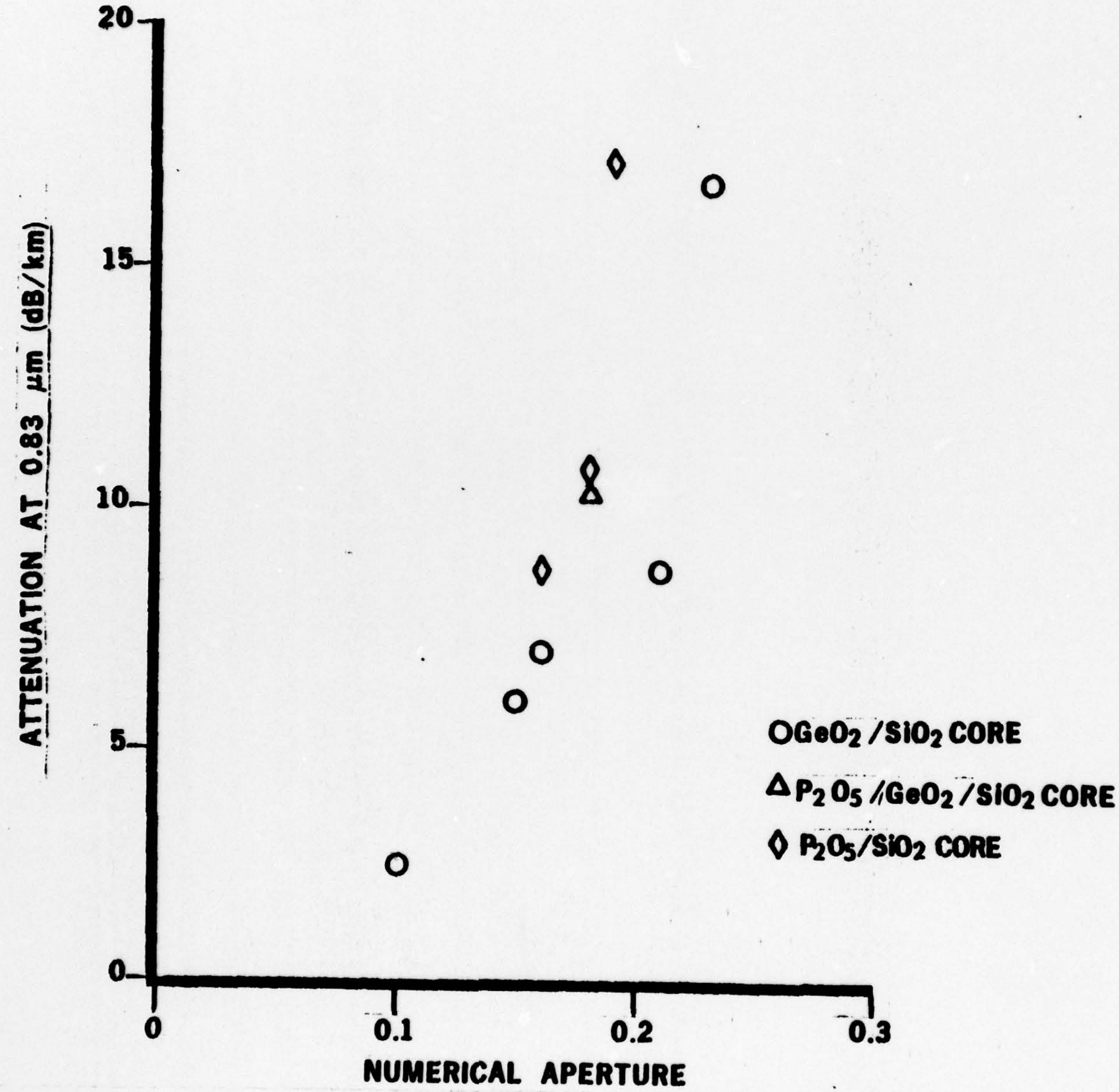

Figure 2. Single Mode Fiber Attenuation vs. NA-Fiber Strung.

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experiments with high NA multimode fibers do not show losses of the magnitude seen here. There is evidence that cladding composition may affect the loss since the 0.1 NA and 0.15 NA GeO_2/SiO_2 core fibers have the same core composition but different cladding compositions. However, the remainder of the fibers in Figure 2 exhibit the NA effect even though they have the same cladding composition. Another possibility is that the excess loss is caused by thermal mismatch of the core and cladding materials, as has been demonstrated for multimode fibers.

2.4.2 Dimensional Evaluation

This task included measurements of the core to fiber OD ratio and the evaluation of nominal fiber diameter and diameter uniformity.

Difficulties in precisely measuring NA and core size coupled with fiber diameter variations make it difficult to reliably predict single mode operation. Examples are EM-20422, EM-20536, EM-20554 and EM-20586 which were multimode at .63 μm in spite of predicted single mode operation from NA and core size measurements. The major design difficulty is associated with core size measurements, which is attributed to the deposition of 4-5 layers of the highly doped core material and the increased control index dip. Dopant diffusion at the core cladding

interface results in a somewhat graded core index which makes it difficult to precisely measure the true core diameters. Also, the central index dip results in inaccurate core diameter measurements.

It was also found that the quality of the broken ends of the cane affected the core size measurement. Jagged or nonuniform breaks on either the injection end or the viewed end causes the core image to vary from the actual size. For example, the cane micrograph of the poorly prepared end of EM-20586 indicated that when the fiber is drawn to a diameter of 116 μm, a core diameter of 2.8 μm would be achieved. However, microscopic examination of the actual fiber revealed a core diameter of 6 μm. Therefore, in order to improve cane fiber measurements, greater care was exercised in end preparation, and measurements were performed on several cane sections for verification.

To evaluate the nominal fiber diameter and diameter uniformity, fibers were cut at 10 cm intervals and the outside diameter was measured with a micrometer.

Table 6 lists the results of fiber diameter measurements for three fibers. The deviation of the mean fiber diameter from the design diameter was found to be <3% for EM-20533 and EM-20536 but >5% for EM-20407. Fiber diameter uniformity is

Table 6. Diameter Uniformity of High NA Single Mode Fibers

Fiber No.	Evaluation Interval (cm)	No. of Samples	Design Diameter (μm)	Mean Diameter Found (μm)	% Std. Dev. Around Mean	% Maximum Deviation
EM-20407	10	30	79	75	2.1%	-4.76%
EM-20533	10	30	71	73	1.65%	+3.03%
EM-20536	10	30	106	105	1.37%	+2.57%

reported as one standard deviation expressed as a percentage of the mean diameter. The nominal diameter variation is enough to cause uncertainty in the single mode cut-off wavelength and to cause higher loss when the fiber is operated near cut-off.

2.4.3 Mechanical Evaluation

Deployment of single mode fibers in coiled configurations will subject them to continuous tensile stress. Also, strength degradation under load will be a factor in sensor lifetime. Strength improvement was not one of the objectives of the study, but mechanical evaluation was performed to determine the effects of furnace drawing on fiber dynamic tensile strength and fatigue characteristics. The mechanical tests discussed in this section include dynamic tensile test, long length proof test and static fatigue test. First, the dynamic tensile tests used variable strain rate control and employed two meter gauge lengths to determine the probability of failure as a function of failure stress. Second, the long length proof test was performed off-line and was used to eliminate rare large flaws in the entire fiber. Third, static fatigue testing was performed on small diameter mandrels in air under ambient conditions, which resulted in determination of the fatigue resistance parameter, N.

The results of the dynamic tensile test are shown as Weibull plots in Figures 3 through 5. A summary of the Weibull

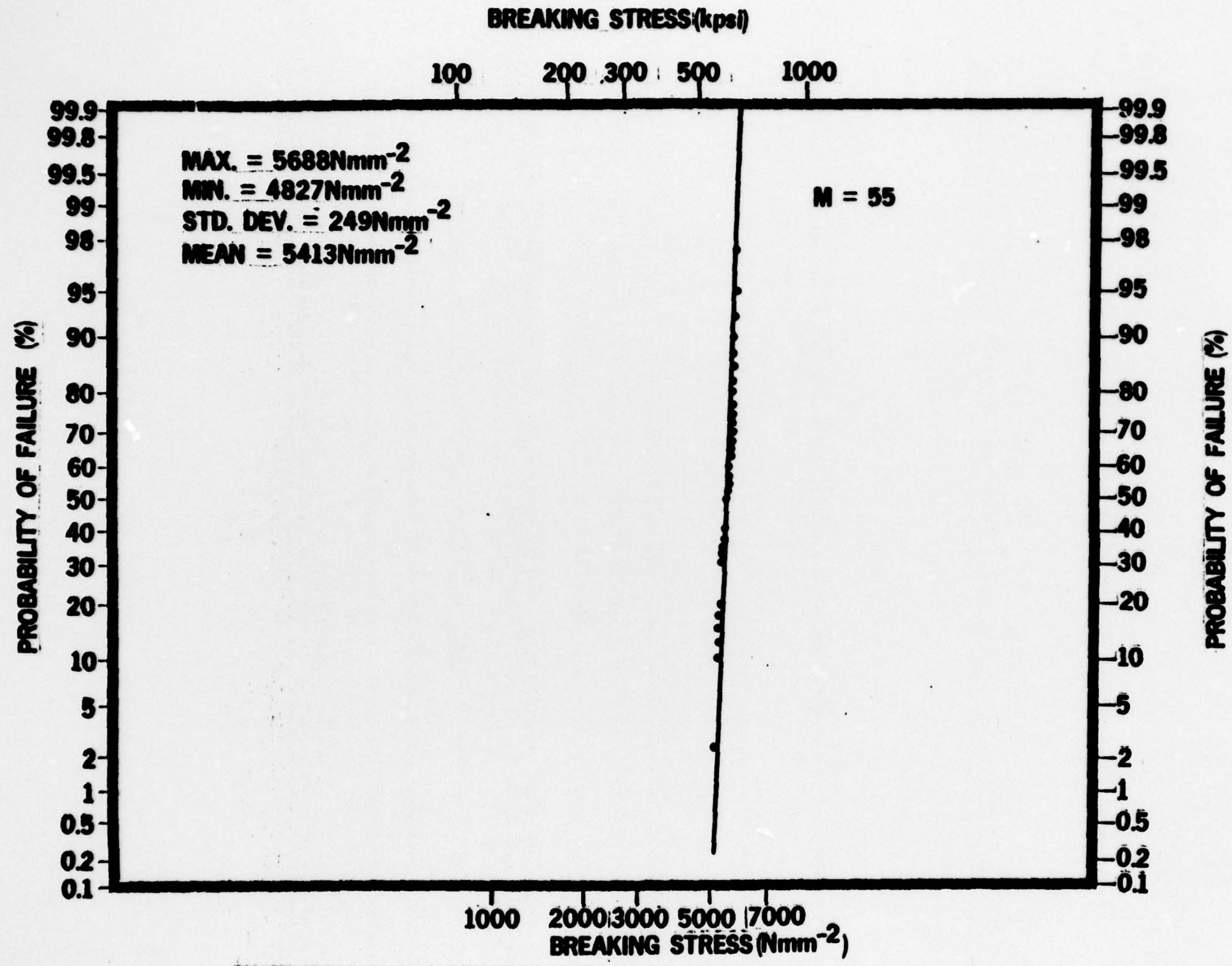

Figure 3. Weibull Plot of SM Fiber EM-20407.

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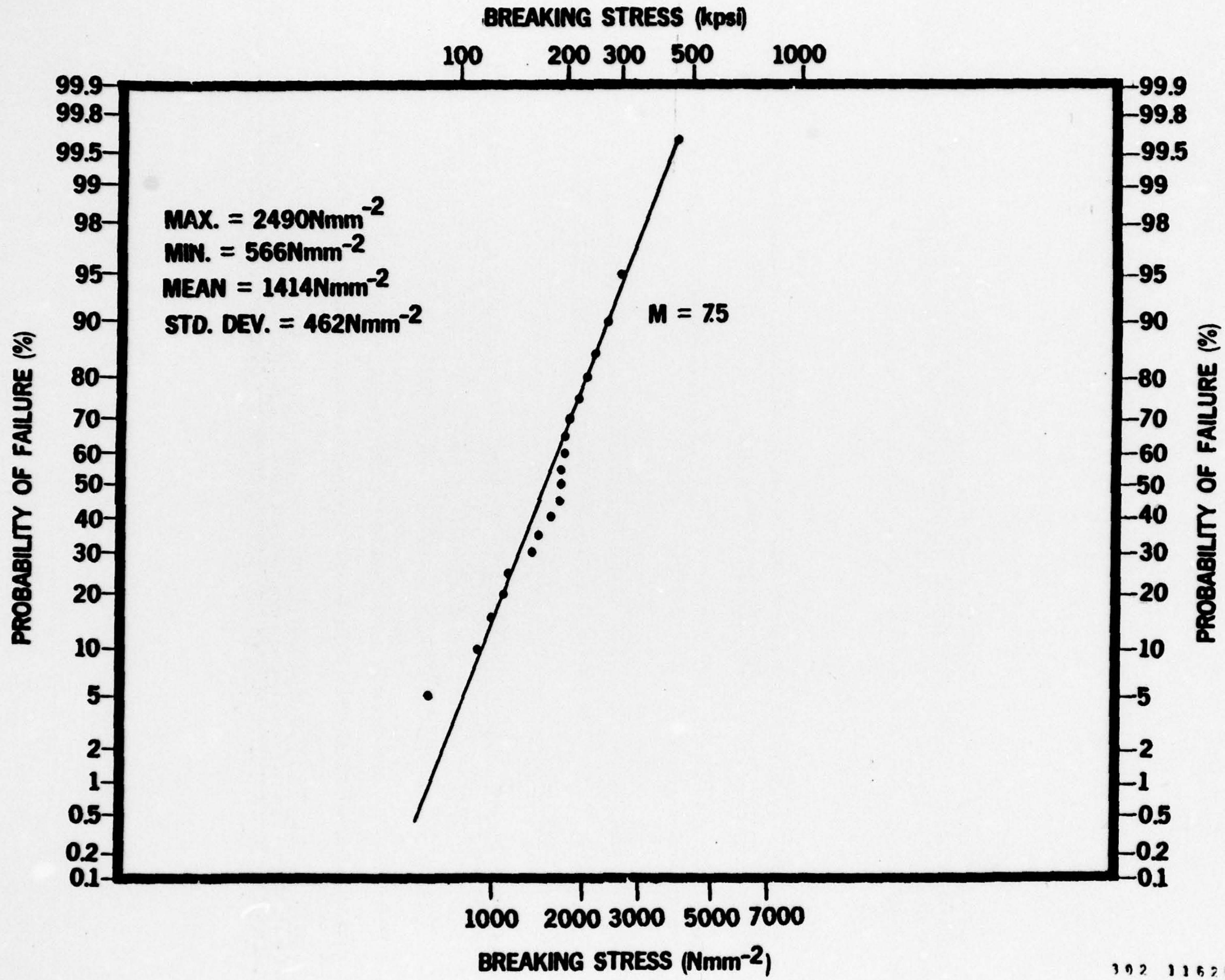

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Figure 4. Weibull Plot of SM Fiber EM-20533.

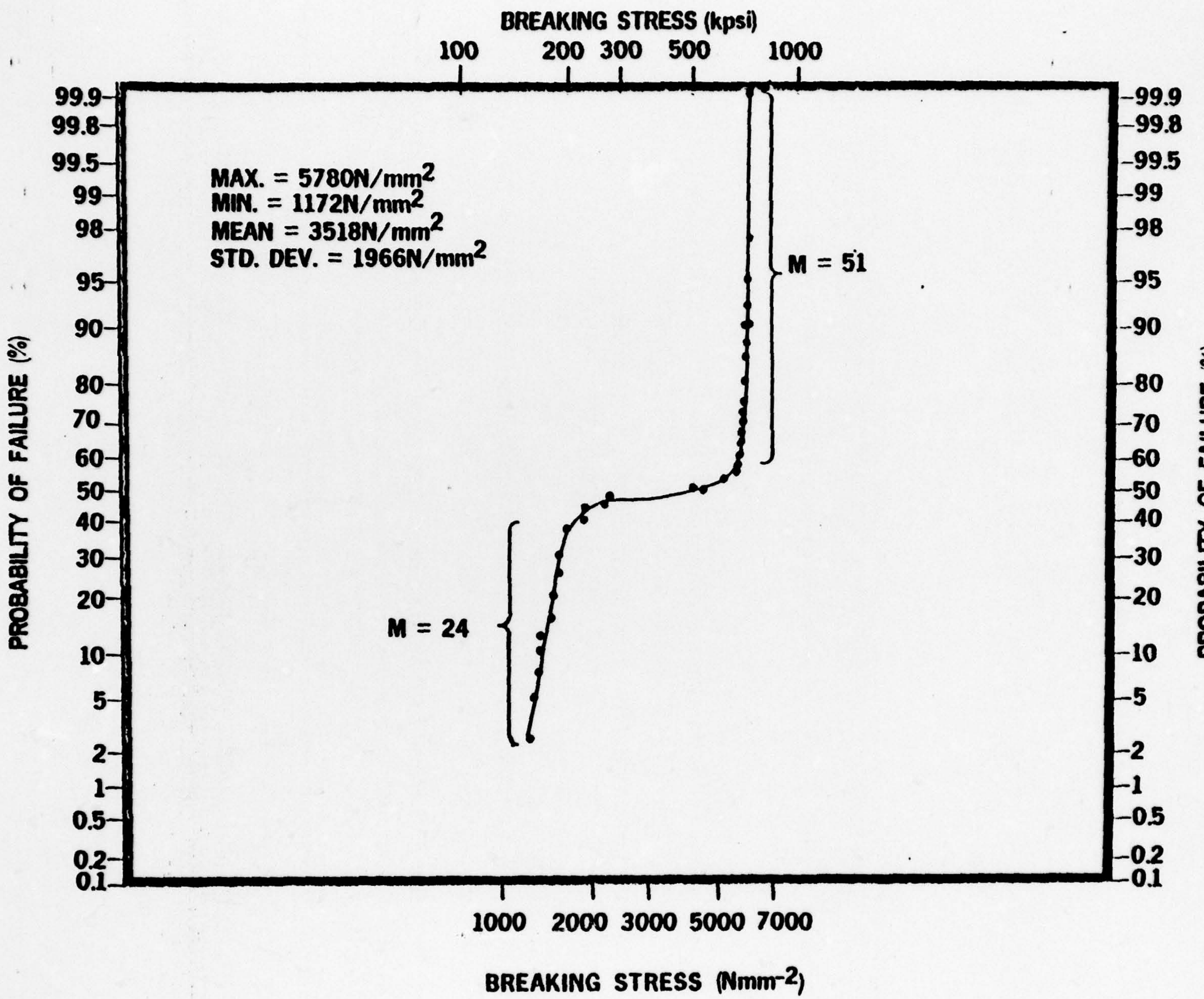

Figure 5. Weibull Plot of SM Fiber EM-20536.

parameters and supplemental long length proof testing results is shown in Table 7.

EM-20407 (Figure 3) shows very high strength with an unimodal distribution of breaking strength. The high mean and minimum strength of 5413 and 4827 N/mm^2 are comparable to values achieved with high strength flame drawn fibers. No large flaws were encountered in the short lengths tested. The long length proof test resulted in one break at 350 N/mm^2 over a 1 km test length. EM-20533 (Figure 4) had a unimodal failure distribution but with a very low slope. In addition, the minimum strength point on the Weibull plot indicates the presence of a "low strength tail." In a 350 N/mm^2 proof test, this fiber broke several times. The low strength results for this fiber were traced to poor jacket concentricity and lumps in the jacket material. EM-20536 (Figure 5) shows a distinctly trimodal failure distribution. Due to the lower strength mode, the mean and minimum strength values are lower than those of EM-20407. In spite of the low strength mode, this fiber did not break during 350 N/mm^2 proof test. Variations in strength from fiber to fiber may be attributed to contaminants in the furnace atmosphere and to nonuniformity in the fiber coating.

The results of the static fatigue tests are plotted in Figure 6. Statistically, fibers EM-20407 and EM-20536 exhibited about

Table 7. Weibull Parameters for Selected Fibers.

Preform No.	Failure Distribution	Maximum Strength (N/mm^2)	Minimum Strength (N/mm^2)	Mean Strength (N/mm^2)	M	350 N/mm^2 PT Breaks/1g (m)
EM-20407	Unimodal	5688	4827	5413	55	1/1000
EM-20533	Unimodal	2490	566	1414	7.5	Numerous
EM-20536	Trimodal	5780	1172	3518	51,24	0/1000

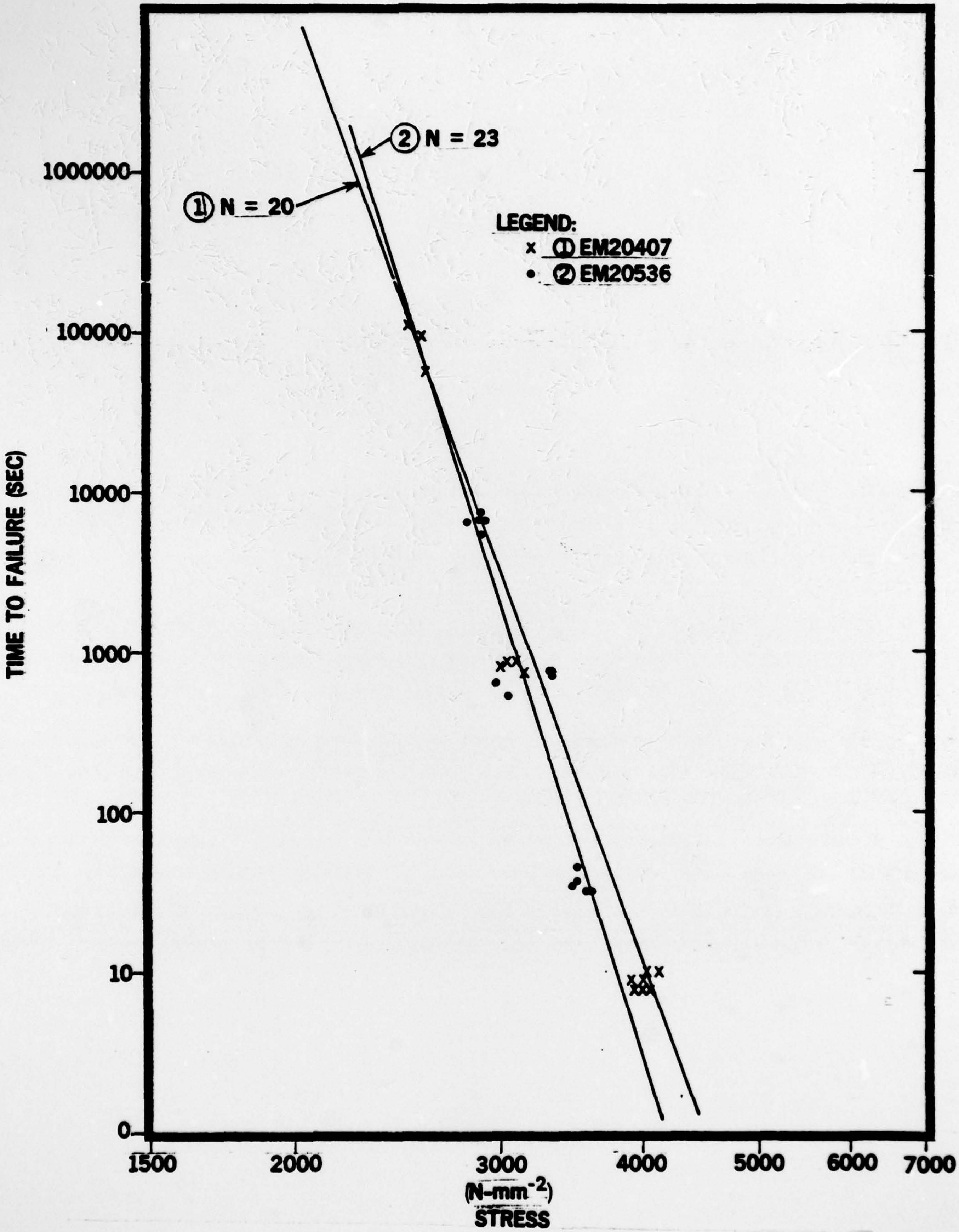

Figure 6. Static Fatigue of SM Fibers in Air.

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the same resistance to fatigue, having N values of 20 and 23 respectively. These results compare favorably with high strength flame drawn fibers for which an N value of 22 is typical.

3.0 CONCLUSIONS AND RECOMMENDATIONS

The experimental effort performed under this program has clearly established that bending and microbending losses in single mode fibers can be significantly reduced if the numerical aperture is increased from .1 to .2. It was also established that a NA = .2 can be achieved with core glass systems of GeO_2/SiO_2, $GeO_2/P_2O_5/SiO_2$ and P_2O_2/SiO_2 surrounded with a B_2O_3/SiO_2 cladding. Evaluation of .2 NA fibers has shown that optical losses in general are higher than those for .1 NA fibers and that the index dip is more pronounced in high NA fibers.

Based on the results achieved and observations made during this contract, EOPD offers the following recommendations to further improve the performance characteristics of high NA single mode fibers.

1. Reduce optical losses in high NA single mode fibers by optimization of dopant concentrations and purity of dopants in the glass systems investigated. This optimization should include a study of the effects of thermal expansion mismatch between core, cladding and substrate glasses on optical loss.
2. Refine fabrication techniques to improve physical and optical properties of single mode fibers. By depositing an increased number of thinner layers of core and cladding glass the non-Raleigh scattering loss is expected to decrease. In addition, the refractive index profile would approach a true

step index and better control of the core clad ratio would be achieved. It is also recommended to develop improved techniques for the reduction of the central index dip. The above described techniques would also improve fiber dimensional control and reproducibility, improve fiber design control, and would result in optical loss reduction.

3. Characterize the functional wavelength range for spooled single mode fibers as a function of NA. This investigation would quantify the relationship observed during the course of this contract between the NA and the wavelength range over which the spooled fiber can be operated without excess bending losses.

4. Characterize the changes in optical transmission which are induced by environmental effects such as temperature and pressure variations.

5. Improve tensile strength of single mode fiber over long lengths. It was shown in this study that high strength can be achieved with furnace drawn fibers over short length. Effort would be concentrated on improving preform fabrication and fiber drawing processes to reduce the incidence of rare large flaws. A vital part of this effort would be the improvement of fiber coating techniques to achieve concentric jackets.